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INTERSTELLAR LINES IN STARS AT HIGH GALACTIC LATITUDES

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ABSTRACT

We have measured the velocity and equivalent widths of the optical interstellar lines in a group of southern B stars at high galactic latitudes, as well as additional data for the stars previously discussed by Münch and Zirin. The main peculiarities of the interstellar matter far above the plane seem to be an increase in the ratio of the column density of Ca II to that of Na I and, less certainly, an excess of Ca II relative to H I. The gas-to-dust ratio indicates that some of the hydrogen at high galactic latitudes may be ionized.
Subject headings: galactic structure — interstellar matter

I. INTRODUCTION

The basic properties of the interstellar medium in the plane of the Galaxy within a 1 kpc of the Sun are known, although many of the details remain somewhat obscure. This is not the case in the direction perpendicular to the plane of the Galaxy; for this region, the observational material is sparse and the nature and amount of the material at high galactic latitudes is unclear. The principal previous optical work has been by Münch and Zirin (1961), Greenstein (1968), and Rickard (1972), while Habing (1969*a*, *b*) combined new radio data with the optical observations in an attempt to elucidate the nature of the gas at high latitudes. Recent suggestions of a large flux of cosmic rays and X-rays in the halo (Silk 1973) as well as the possible existence of a more massive halo (Ostriker and Peebles 1973) make it imperative that we try to obtain more data on the interstellar medium above the plane of the Galaxy.

The difficulty of the problem is compounded by the scarcity of O and B stars at large galactic latitudes high above the plane. Furthermore, to get high up in the halo, one needs the fainter stars and then one must avoid the less luminous horizontal-branch B stars, which are difficult to distinguish spectroscopically from B stars of normal luminosity. We have therefore restricted ourselves to stars brighter than $V = 8.5$ mag chosen from the list by Hill (1971) of southern B stars at intermediate and high galactic latitudes with detectable interstellar Ca II lines.

II. COLOR EXCESSES

We list in table 1 the program stars, their height above the plane (Z), the distance (S) along the line of sight which falls within the disk (defined to have a half-thickness of 100 pc), the color excess, and the radial velocity in the local standard of rest (LSR) system of the observed interstellar lines. The color excesses were calculated from the spectral types and *UBV* colors given by Hill (1970) and the calibration of Schild, Peterson, and Oke (1971). Several of the stars studied by Münch and Zirin (1961) do not have previously measured *UBV* colors. These were kindly measured on the *uvby* system by J. Barnes at Kitt Peak. If we assume the standard gas-to-dust ratio that prevails in the plane, then we may derive $N_{\rm H}$ from $N_{\rm H}/E_{B-V} = 5\ 10^{21}$ atoms cm^2 mag^{-1} (Jenkins and Savage 1974), assuming an uncertainty in E_{B-V} of ± 0.03 mag. In a few cases, we have 21-cm data from Heiles and Habing (1974) which yields $N_{\rm H\,I}$. We compare the observed radio values with those computed from the reddening in table 2.

Except for HD 35575 and HD 29248, where probably most of the gas is behind the star, the agreement between $N_{\rm H}$(optical) and $N_{\rm H\,I}$(radio) is not unreasonable. However, if we examine only the stars with $E_{B-V} \geq 0.1$ mag, four of the five stars (all more than 750 pc above the plane) have $N_{\rm H}(E_{B-V})/N_{\rm H\,I}$(radio) $\approx$ 2. These four are located relatively close together at negative galactic latitudes with $l^{\rm II}$ near 50°. The exception is almost certainly due to a cloud close to the plane on the line of sight to HD 149363. If we compare these data with the ratio of neutral hydrogen from

TABLE 1

High Latitude Southern Stars

Star	Z (pc)	S (pc)	E_{B-V}	V^{i}_{LSR} (km/sec)
HD 10747	720	150	+0.05	-14
HD 22586	1600	130	+0.09	+ 6
HD 24757	370	140	0	- 6
HD 35575	150	300	+0.03	0
HD 43071	140	250	0	+18
HD 84971	700	170	+0.04	*
HD 120086	1700	120	+0.03	*
HD 149363	1500	220	+0.27	*
HD 170385	230	380	+0.05	- 5
HD 173994	270	300	+0.09	- 1
HD 203532	105	180	+0.27	+ 6
HD 209522	200	125	0	- 3
HD 214080	2700	120	+0.16	- 3
HD 220172	750	110	0	- 1

*Velocities not measured on image tube spectra

* Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

TABLE 2

Optical and Radio Column Densities of Hydrogen

Star	N_{HI}	N_H from E_{B-V}	Z (pc)
HD 35575	1 10^{21}	2 10^{20}	150
HD 84971	2 10^{20}	2 10^{20}	700
HD 120086	3 10^{20}	2 10^{20}	1,700
HD 209522	1 10^{20}	≤ 2 10^{20}	200
HD 214080	3 10^{20}	6 10^{20}	2,900
HD 220172	3 10^{20}	≤ 2 10^{20}	750
Stars from Münch and Zirin			
HD 29248	6 10^{20}	2 10^{20}	240
HD 97991	6 10^{20}	2 10^{20}	640
HD 104337	3 10^{20}	≤ 2 10^{20}	280
HD 149363	1 10^{21}	1 10^{21}	1,500
HD 203664	3 10^{20}	1 10^{20}	660
HD 206144	2 10^{20}	3 10^{20}	1,200
HD 215733	3 10^{20}	5 10^{20}	1,200
HD 219188	4 10^{20}	7 10^{20}	900

Lα versus E_{B-V} (Jenkins and Savage 1974), we find that there are many points below the mean by a factor of 2. In most cases this may be due to molecular hydrogen, but such an explanation is not tenable for high-galactic-latitude stars. One would also not expect peculiarities in the grains large enough to cause such a change in the ratio $E_{B-V}/N_{\text{H I}}$. Perhaps in these cases the hydrogen is ionized. However, in no case is the discrepancy greater than a factor of 2. Therefore, although some of the gas above the plane may be ionized, most of it may well be normal. Knapp, Kerr, and Rose (1973) conclude that most of the gas is in the form of neutral hydrogen, as is the case in the plane.

III. SPECTROSCOPIC OBSERVATIONS

The program stars were observed spectroscopically with the 1.5-m telescope of Cerro Tololo Inter-American Observatory at dispersions of 9 Å mm^{-1} for baked IIa-O plates and 18 Å mm^{-1} for 098-02 exposures centered at 6000 Å. Intensity tracings were prepared by using spot-sensitometer calibrations exposed simultaneously with the spectra and the PDS microphotometer of Kitt Peak National Observatory. In general the yellow plates were somewhat underexposed.

Radial velocities were measured for all interstellar features with an oscilloscope Grant comparator. These radial velocities, corrected to the LSR system, are given in table 1. We have two stars in common with the higher-dispersion survey of Münch and Zirin. In each case, our V_r corresponds to the V_r of the strongest components that they saw. We did not clearly resolve the weaker components (estimated to be one-fourth and one-third the strength of the main component) that they observed, although we could see that the line was composite. We saw hints of additional components with a strength of about one-third that of the principal line and with V_r approximately $+20$ km s^{-1} from the main line in HD 220172 and HD 170305, while HD 173994 appears to have a component with $V_r \approx -20$ km s^{-1} from the main line. In HD 22586 and HD 35575, the interstellar Ca II profiles are asymmetrical, but the situation is confused by the presence of stellar Ca II features. The resolution at the sodium D lines is insufficient to see the component structure.

A few additional stars from the list of Münch and Zirin (1961) were observed during the winter of 1973–1974 at Kitt Peak with the coudé auxiliary feed and an image-tube system giving dispersions of 3 Å mm^{-1} in the blue and 4 Å mm^{-1} in the red. Also, four stars were observed with the Wisconsin echelle spectrograph and a two-stage Carnegie image tube on the 4-m telescope at Kitt Peak. Details of the design of this instrument can be found in Schroeder and Anderson (1971). The entrance slit was 50 μ by 0.5 mm or 100 μ by 0.5 mm, and the hollow-cathode comparison lines had a full width at half-maximum of 0.2–0.3 Å. None of the image-tube spectra were measured for radial velocities, and the resolution is not adequate to delineate clearly the component structure. Certainly there are no components not noted in the tables whose strengths were more than one-third that of the central peak with a V_r difference of more than 10 km s^{-1} from that of the central peak, with the possible exception of HD 120086, which may have two approximately equal components with a velocity difference of about 20 km s^{-1}.

Equivalent widths were measured for the Na I doublet at 5900 Å and the Ca II H and K lines, although in many cases λ3968 was badly blended with Hϵ. In cases with obvious component structure, we tried to measure only the principal component. There were no molecular features in any of the spectra that were strong enough to be detectable. The equivalent widths are given in table 3.

From the doublet ratios, we derive the column densities and Doppler velocities listed in table 4 using the curve of growth for a single cloud with a Gaussian velocity distribution given by Münch (1968). In many cases λ3968 of Ca II was too badly blended with Hϵ to be measured. Under such circumstances, the following prescription was used to derive the Ca II column density. If $W_\lambda(3933)$ is less than 90 mÅ, the doublet ratio is assumed to be 2.0. For $W_\lambda(3933)$ greater than that, we assume that the doublet ratio is 1.4. This corresponds to a Doppler width of 5 km s^{-1} for $W_\lambda(3933) = 150$ mÅ and 9 km s^{-1} for) $W_\lambda(3933) = 200$ mÅ. This choice was made to correspond to the Doppler widths seen in the plane for such ranges of values of W_λ for the Ca II interstellar lines. If anything, we have underestimated the column density of Ca II by overestimating the Doppler width and hence underestimating the saturation of the lines.

We note that the widths of the interstellar lines look completely normal, namely, the weaker lines are unresolved on spectra at 9 Å mm^{-1}.

IV. DISCUSSION

We do not intend to speculate on the nature of ionization at high galactic latitudes, and shall there-

TABLE 3

Equivalent Widths of Interstellar Lines

	V_{LSR}	K	H	D_2	D_1
High Galactic Latitude Southern Stars:					
HD 10747		235			
HD 22586		150			
HD 24757		185			
HD 35575		70		240	155
HD 43071		150		100:	75:
HD 84971		100		180	130
HD 120086		180:		110	60
HD 149363		90		160	120
HD 170385		185			
HD 173994		225		310:	235:
HD 203532		150		280	280
HD 209522		50		45:	12:
HD 214080		165	130:	250	160
HD 220172		215	85:	75:	20:
New Data for Stars from Münch and Zirin:					
HD 29248	+21	80		80	60
	+ 2.5	20		40:	30:
HD 38666	+20.9 +40.1	} 150		40	
				30	
HD 97991		65		120	70
HD 104337		105		85	
HD 203664	+ 2	250[2]	185	175	130
	+76	88	63	< 40	
HD 215733	-57	51[2]	26[2]	} 270	160
	-44	85	46		
	-26	90	55		
	-11	106	72		
HD 219188		140[1]	70[1]	220[1]	190[1]

Notes: 1 - main component only
2 - W_λ for various velocities from Münch and Zirin (1961)

fore not attempt to derive total calcium and sodium abundances. With regard to photoionization, Zimmerman (1965*a*, *b*) has derived the radiation field at high galactic latitudes for Z up to 250 pc, and we have extended his calculation to 2 kpc above the plane. The ultraviolet radiation field at 1 kpc is within a factor of 4 of that in the plane. This would imply, if the material is photoionized in relatively thin clouds, that Na I/Na will increase proportionally to the decrease in Γ (the probability of photoionization of a ground-state atom per second), as it is so large in the plane, while the Ca II/Ca may increase more slowly than the decrease in Γ, as Ca II may already be 10 percent of the calcium in the plane. Therefore, for photoionization in clouds similar to those in the plane, we predict Ca II/Na I the same as or slightly smaller (for a constant n_e) than the mean value for the plane. We will see later that this is not what is observed. Reduction of n_e produces the same effect as increasing Γ, namely, Ca II/Na I is constant.

Let us examine the data of table 4 to see if there is any way of determining that we are not looking in the plane. We pay particular attention to the stars marked with an asterisk, as they are the ones with $Z \geq 550$ pc. The most outstanding peculiarity is that the values of Ca II/Na I tend to be larger by at least a factor of 4 than the mean values for the plane (an average of my determination [Cohen 1973] with that of Jenkins and Savage 1974). This is a well-determined parameter, and the change must be real. Routly and Spitzer (1952) predict that this will occur in H II regions due to collisional ionization of Na I. We note that Hobbs (1974) finds that in the plane Na I/H I becomes smaller as H I becomes smaller, which is an effect similar to that we are seeing. We now ask: Is the Ca II overabundant, or is the Na I deficient? This is a more difficult question, as the H I values are not exactly comparable to the optical values, there may be gas behind the star, although that does not seem reasonable for stars beyond $Z = 550$ pc, and the beam size of the radio surveys is much larger. Assuming that the gas is not concentrated in very small clouds, it does appear that in the majority of cases Ca II/H I is large, rather than Na I/H I.

Therefore, the two peculiarities that we see are the following: Ca II/Na I is about a factor of 4 greater than the mean value for the plane, and Ca II/H I is larger than in the plane, whereas Na I/H I is closer to the mean value for the plane.

We are now ready to face the question of where in Z this gas is located. Are we seeing the tail end of clouds in the plane at a height of perhaps 100 pc, or are we really seeing gas at significantly larger values of Z? Münch and Zirin (1961) and Rickard (1972) concluded that at least some of the components they saw were at Z greater than 500 pc. We agree, as we see in the low-Z stars gas which in some cases is identical to that in the plane, whereas for the higher-Z stars the interstellar gas shows definite peculiarities.

V. SUMMARY

We have shown by comparing the color excesses and radio observations at 21 cm for stars above the plane that the ratio $N_{\mathrm{H\,I}}/E_{B-V}$ appears to be peculiar in the few stars with $E_{B-V} \geq 0.1$ mag, so that some of the hydrogen may be ionized, although the less reddened stars do not seem to show this abnormality. We must note, however, that $N_{\mathrm{H\,I}}$ and E_{B-V} may be dominated by a single component close to the plane. The interstellar lines have low velocities in the LSR system, and the line strengths of H and K and the D lines are mostly normal in the stars with low values of Z. For the stars with large values of Z ($Z > 550$ pc), we see two peculiarities: Ca II/Na I is about a factor of 4 larger than in the plane; and, less certainly, it is Ca II which is overabundant relative to neutral hydrogen rather than Na I being deficient. We also conclude that at least some of the interstellar gas we are observing is at large values of Z. Observations at higher resolution to resolve the component structure and in the ultraviolet to detect the ionized regions would be very useful.

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TABLE 4

Column Densities

Star	V_{LSR}	N_{CaII}	N_{NaI}	N_{HI}	CaII/NaI	CaII/HI	NaI/HI
Southern Stars:							
*HD 10747		12.7		20.4 E		-7.7	
*HD 22586		12.5		20.6 E		-8.1	
HD 24757		12.6					
HD 35575		11.8	12.3	20.6 H[1]	-0.5	-8.8[1]	-8.3[1]
HD 43071		12.5	12.1		+0.4		
*HD 84971		12.2	12.3	20.3 H	-0.1	-8.1	-8.0
*HD 120086		12.6	11.9	20.5 H	+0.7	-7.9	-8.6
*HD 149363		12.0	12.3	21.0 H	-0.3	-9.0	-8.7
HD 170385		12.6					
HD 173994		12.7	12.6		+0.1		
HD 203532		12.5	>12.4		<+0.1		
HD 209522		11.7	11.4	20.0 H	+0.3	-8.3	-8.6
*HD 214080		12.7	12.4	20.4 H	+0.3	-7.7	-8.0
*HD 220172		12.4	11.6	20.2 H	+0.8	-7.8	-8.6
Stars from Münch and Zirin (1961):							
HD 29248	+ 6.8	11.9	12.0	20.8 Ha[1]	-0.1	-8.9[1]	-8.8[1]
	-11.7	11.3	11.7	<20.0 Ha[1]	-0.4		
HD 38666	+ 4.4	12.2[3]	11.3		+0.9		
	+23.6	12.1[3]	11.2		+0.9		
*HD 91316	-15	11.8	11.8	20.7 Ha	+0.1	-8.8	-8.9
	- 5.5	11.3					
	+14.4	11.5	11.3	20.3: Ha	+0.2	-8.8	-9.0
*HD 93521	-55	11.8		20.1 Ha		-8.3	
	-34	11.3	11.0	≤19.9 Ha	+0.3		
	-10	12.2	12.4	20.1 Ha	-0.2	-7.9	-7.7
	+ 7	11.5		≤19.9 Ha			
HD 97991		11.8	11.9	20.6 Ha	-0.1	-8.8	-8.7
HD 104337		12.1	11.6	20.5 H	+0.5	-8.4	-8.9
*HD 203664	+ 2	12.8	12.3	20.5 H	+0.5	-7.7	-8.2
	+76	12.3	<11.3	≤19.5 H	>+1.0	≥-7.2	
*HD 215733	-51	11.7		19.6 Ha		-7.9	
	-38	12.0	12.2	19.6: H	+0.2	-7.6	
	-20	12.0		19.7 H		-7.7	
	- 5	12.4		20.5 H		-8.1	
*HD 219188	- 4	12.2	12.7	20.6 H	-0.5	-8.4	-7.9
Average Plane					-0.4	-8.8	-8.4

Notes: * - Stars with Z >550 pc.
1 - Much of H I may be behind the star.
2 - W_λ from Münch and Zirin (1961) for HD 91316 and HD 93521.
3 - Observed Ca II W_λ proportioned among component by intensities in Münch and Zirin (1961).
E - N_{HI} from observed color excess.
H - N_{HI} from Heiles and Habing (1974).
Ha - N_{HI} from Habing (1969).

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